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STUDY OF COMMAND AND CONTROL (C&C) STRUCTURES ON THE EMPLOYMENT OF COLLABORATIVE ENGAGEMENT CAPABILITY (CEC) ON LAND SYSTEMS

by

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September 2012

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CEC has yet to be employed on any land combat systems. This thesis discusses possible employment of CEC on land combat systems based on a combat operational profile. Simulation analysis on a land-based anti-air defense scenario provides insights on the employment of CEC on land combat systems.

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STUDY OF COMMAND AND CONTROL (C&C) STRUCTURES ON THE EMPLOYMENT OF COLLABORATIVE ENGAGEMENT CAPABILITY (CEC) ON LAND SYSTEMS

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ABSTRACT

Cooperative Engagement Capability (CEC) is employed by the United States Navy (USN) to allow combat naval systems to share combat resources, collectively gather and distribute intelligence data and generate superior air pictures for effective and efficient engagement against air threats with high precision, timeliness and accuracy using existing radar or weapon systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

BDE	Brigade
BOE	Back of Envelope
C&C	Command and Control
CBG	Carrier Battle Groups
CEC	Cooperative Engagement Capability
COP	Common Operational Picture
DIV	Division
DOE	Design of Experiment
HIMARS	High Mobility Artillery Rocket System
HQ	Headquarters
M&S	Modeling and Simulation
NCW	Network-Centric Warfare
OODA	Observe-Orient-Decide-Act
SA	Situation Awareness
SD	Standard Deviation
S/N	Signal to Noise
TPQ	Weapon Locating Radar
USN	United States Navy

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EXECUTIVE SUMMARY

Cooperative Engagement Capability (CEC) is a capability that integrates all data gathering/sensor resources to track and transmit critical information to all connected platforms, thereby generating a common Situation Awareness (SA) picture. Other than providing a common SA picture, CEC allows increased accuracy and timeliness of time-critical data such as incoming enemy missiles; this allows an appropriate weapon system to effectively destroy the threat. With time being a critical factor in such operations, it is vital to minimize delays resulting from Observe-Orient-Decide-Act (OODA) loops. The solution seems to be a large number of units networking as a single, distributed and defensive/offensive system. This CEC concept has been developed since the early 1970s, with live firing completed on June 2004 (Hopkins, 1995).

However, CEC has not been employed in land combat systems. Despite several distinct differences between land combat forces and naval combat forces, there are several operations where land combat forces could leverage the capabilities of CEC to increase offensive and defensive capabilities. One such area is anti-air defense systems.

This thesis studies the potential use of CEC in land systems. Back of Envelope (BOE), ExtendSim simulations using Taguchi design were performed on three types of air threats: (1) mortar bombs, (2) artillery shells and (3) rockets fired against an anti-air defense system consisting of radar and anti-air weapon. From the results, it was noted that the implementation of CEC would be more

effective in anti-air defense against artillery shells and mortar bombs. For that reason, rockets will not be tested in ExtendSim. Also, from the results of the BOE as well as the need to test the CEC capabilities on land combat forces, four control variables were identified: (1) detection range, (2) maximum engagement range, (3) process time and the (4) number of concurrent air targets that the anti-air weapon system can engage at one time. The two noise variables are fired range and rate of fire of the air threats. With four levels of control variables and two levels of noise levels, a total of 320 simulation runs were performed. The mean plots for both mortar bombs and artillery shells are shown in this thesis.

From the simulation results, it is noted that process time is key to the success rate of intercepting incoming air threats. Process time refers to the rate of information transfer between the weapon location radar (TPQ) and anti-air weapon. This includes the data processing at the TPQ, analysis by the TPQ commander, data transfer (either wired or wireless) between the TPQ and anti-air weapon, decision making by the Division/Brigade commander and execution by the anti-air weapon commander.

Other factors such as detection range, maximum engagement range and number of concurrent targets to be engaged were determined to have little influence on the interception rate of the air threats. Nonetheless, the interception rate is also much dependent on the rate of fire and range of the air threats. The interception rate of rockets is noted to be high due to the long range from which they are fired, which increases the anti-air

engagement window and small quantity of the rockets fired upon a target. Air threats from artillery and mortars pose potential threats to the land targets and limit the anti-air engagement window. Taguchi analysis shows mortar bombs to be the most dangerous threat, as the maximum interception rate was only about 83%.

In conclusion, land combat forces can employ CEC to increase SA among the troops, increase interception rate and reduce process time. However, the implementation of CEC on land systems cannot be taken wholesale from the CEC structure used in the U.S. Navy (USN) due to the differences in threats, operations, platforms and cost of CEC equipment and implementation. Thus, it is recommended to implement relevant functions of CEC by focusing on adjusting the network connectivity structure and rapid data processing rate of CEC to suit the needs of the land combat forces. These needs include the reduction of process time, increased interception rate of incoming air threats and, lastly, reduction of cost. Exploration of doctrinal changes to reduce OODA loop delay time should also be continued.

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I. INTRODUCTION

A. PROBLEM DESCRIPTION

1. Cooperative Engagement Capability (CEC)

Warfare has never been so complex, having budding relations with social economics, emergence of information technology and powerful dynamics of business processes and organizations. The expertise generated in these areas helps to formulate better warfare fighting concepts with three changes: (1) a shift in focus from the platform to the network, (2) priority on integration between humans and systems and (3) a more strategic perspective that adapts and survives in a changing environment and context. Essentially, these changes propel the evolution of platform-centric warfare to network-centric warfare (NCW), which allows our forces to develop speed of command. Information superiority with better awareness is one of the key advantages of speed of command. However, achieving this advantage of speed of command requires superior sensors, powerful networks and display technology (Cebrowski, 1998).

CEC leverages the concept of NCW and speed of command to optimize combat power against threats by (1) pooling multiple existing sensor resources to increase track accuracy and sensor range, (2) upgrading networks and displays for real-time information transfers, and (3) establishing a common combat picture (Stein, 1998).

Since the employment of CEC in the USN is technically effective through the use of superior situation awareness (SA), as well as NCW, combined combat power and speed of command are keys to obtain precise, timely and accurate

threat information to counter air threats. However, are these concepts and employment of CEC applicable for Land systems? Will CEC be as effective on land systems as it is on naval systems?

2. Decision Making Time

One of the key activities of CEC is the target engagement process. This process requires a target to be detected and identified by sensors (radars, human intelligence, Unmanned Reconnaissance Vehicles, etc.). Once the sensors have obtained the target's location, engagement weapons will be selected to engage the target. The target engagement process relies heavily on the Command and Control (C&C) structure as it is an iterative and critical process of decision-making, and is time consuming due to the need to observe, orient and process a variety of conditions and information (validity and accuracy of information, engagement resources, time available to engage, consequences of engagement and not engaging, Rules of Engagement, safety of own forces, engagement authorization, etc.) logically by a computer and rationally by a commander before making a decision. The target engagement decision-making process is commonly known as the Observe-Orient-Decide-Act (OODA) loop, developed by Boyd (1987).

The OODA loop was often used to describe a decision maker's process in a generic situation. In order to present a more representative model of various forms of combat, a modified OODA loop was created (Figure 1). This includes various factors that influence the orientation of the decision maker, creating multiple loops. OODA models have

been constantly analyzed and evolved in a cybernetic approach on C&C. After various developments, examples such as Lawson's model and Wohl's model were introduced. Common to these models was the conclusion that time is the dominant concern in warfare (Brehmer, 2005).

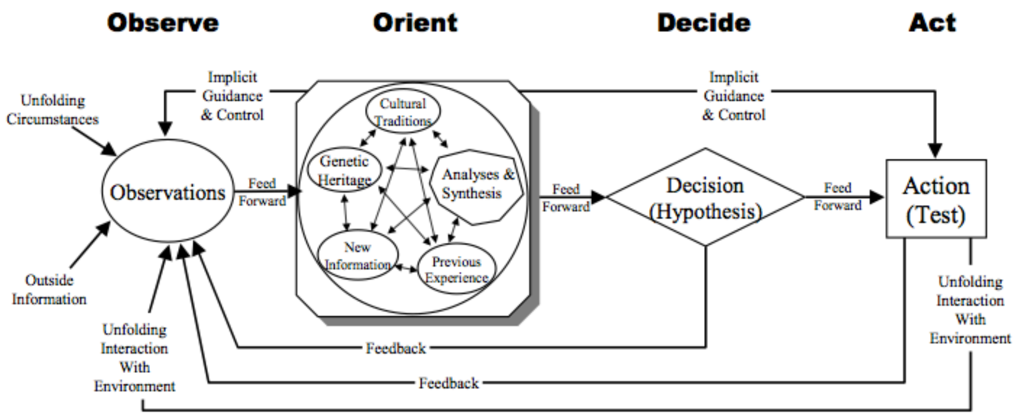

Figure 1. Boyd's OODA loop (From: Boyd, 1996)

One possible framework that could encapsulate the OODA loop is the integration framework.

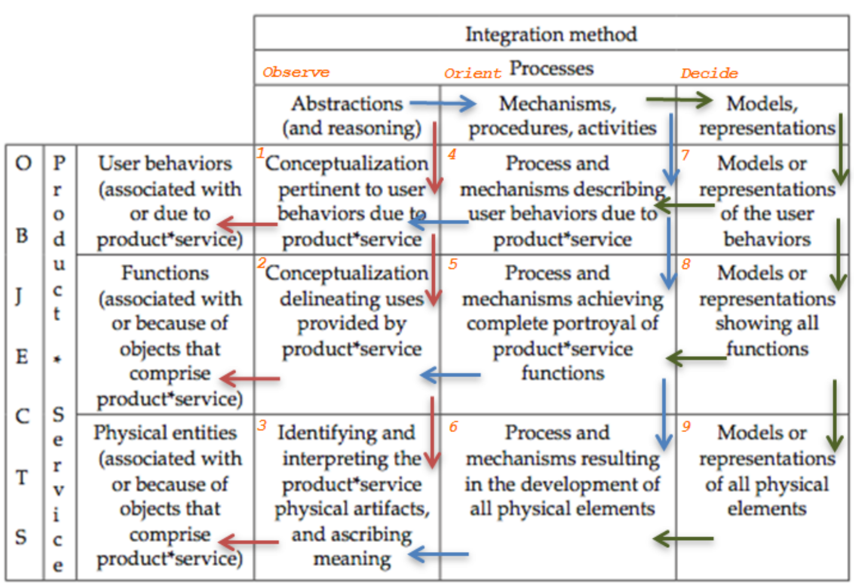

Figure 2. OODA loop using integration framework (From: Langford, 2012)

In the processes domain, abstractions, mechanisms and models can be represented by observe, orient and decide of the OODA loop, respectively. The act of the OODA loop is essentially the interaction of the objects, which is on the objects domain of the integration framework. In a scenario where a commander is tasked to engage a target, he would envision how the task would be accomplished. The commander would observe and expect that the target is armed, know the functions that he needs (e.g., to shoot or call for fire) and identify the type of hardware (equipment such as rifle) and software (soft tools such as communications network) required to accomplish the mission, and these are indicated in box 1, 2 and 3, respectively. Upon the completion of the observe/abstractions column, the commander shifts to the next column (box 4, 5 and 6), orient/mechanism where he establishes procedures in the objects domain to follow in order to align to the observe/abstractions column. Lastly, he would act (engage the target) based on the realization of the integration of preplanned and established behaviors, functions and objects through observe, orient and decide column.

a. Delays

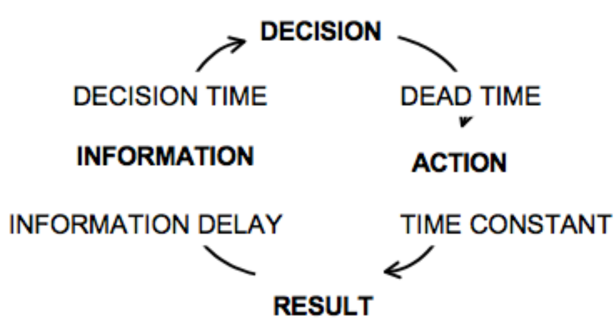

Figure 3. Sources of delay in dynamic decision loop (From: Brehmer, 2005)

However, reducing the delays in the dynamic OODA loop is just one of the factors for winning wars in military warfare. Another approach would be to disrupt the enemy's dynamic OODA loop by increasing their decision-making time, reducing their certainty of what is observed (such as unsound tactical maneuvers), or displaying activities that are unforeseen (such as deception). Operating "inside" an opponent's OODA loop means acting quickly to outthink, to outmaneuver, to use the situation to your advantage, and to exploit the opponent's weaknesses. Whether by reducing delays or disrupting decision-making, time is a dominant concern in military warfare (Brehmer, 2005). With references to military theory and concepts, the dynamic OODA loop (Figure 4) was developed to capture the condition of 'system shock' (i.e., acting fast and decisively in order to win wars).

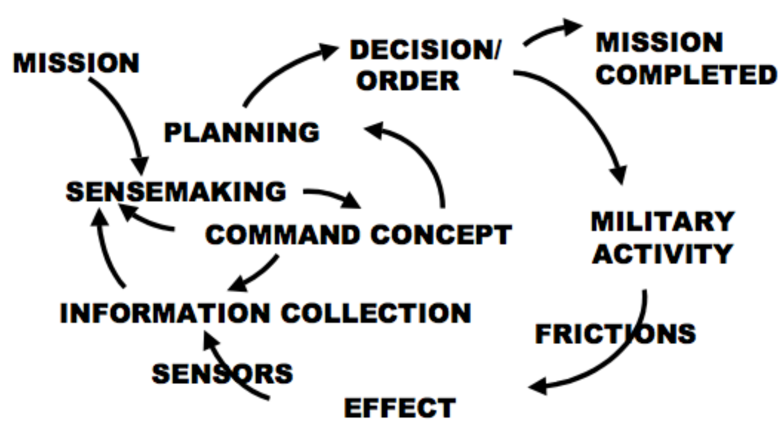

Figure 4. Dynamic OODA loop (From: Brehmer, 2005)

Through this understanding of the OODA loop development of the decision-making process in various models, it is key for decision makers to have more time to process the chunks of information gathered, rationally

assess the overall situation, build SA, issue commands and allocate time for their execution. However, this luxurious warfare attribute is seldom achievable in reality due to the scale and complexity of modern warfare, cluttered combat zones, unforeseen situations, and time-critical events as well as overload of unfiltered information. However, the quest for time advantage by shortening the delays could affect the quality of the decision; thus, one may use that time advantage to increase the decision-making process time instead (Brehmer, 2004).

b. Quality of Information

The OODA loop described the process of decision-making; however, the quality of decision made is the final output and will ultimately and directly affect the outcomes.

Making a quality decision requires a chain of links/inputs (Figure 5). These inputs can be categorized as (1) knowledge (inputs 1-3), (2) perspective (input 4), (3) logic (input 5), and (4) action (input 6).

Figure 5. Six elements of decision quality (From: Spetzler, 2007)

The knowledge required for a quality strategic decision requires a conscious effort to establish both a defined scope and a clear purpose for a team of decision makers from various backgrounds, who are able to explore various possibilities and alternatives from information that is reliable and accurate. Through the generation of alternatives, trade-off analysis must be performed for the various perspectives to be aligned. These perspectives represent the principles and fundamental values of the organization that is making the decision. It is with the consideration of knowledge and perspective that a logical reasoning can be made. However, it is the commitment from all involved parties to implement the decision that significantly influences that decision's ultimate quality. Thus, the quality of the decision does not lie with the decision maker alone, but also with his team and involved members. Therefore, the quality of decision is only as good

as the weakest link. If there is no meaningful and reliable information, the quality of decision could be as good as anyone's guess (Edwards, Miles, & Von, 2007).

From the earlier discussion, time and the quality of decision are undeniably important in time-critical situations. The employment of CEC in the USN embraces the concept of OODA by reducing delays to gain time through the target-engagement process, which includes the decision-making process. Will time be equally important in the land combat environment as it is at sea, when CEC is employed in time-constrained situations? Does the time gained from employing CEC provide the land combat forces with a better chance of winning?

3. The Goal

The goal of this thesis is to accomplish four tasks. First, study the concept of CEC. This research will identify key capabilities that are employed by the USN in its operations. Second, analyze how land combat forces could employ CEC in their operations. Third, conduct simulation analysis on land combat operations using CEC to determine the importance of time and benefits of employing CEC. Fourth, provide recommendation of the feasibility of employing CEC in land combat forces with suggestions for further analysis and research.

4. Thesis Organization

This thesis consists of six chapters.

Chapter I describes the problem and establishes specific goals for this thesis.

Chapter II studies the benefits of employing CEC. It explains in detail the CEC capabilities.

Chapter III analyzes the effect of employment of CEC on land systems through the study of the operating environment, followed by possible land operations that would benefit from the capabilities of CEC.

Chapter IV introduces the tools that would be used in the simulations. This sets the framework for the analysis of the results in the following chapter.

Chapter V presents the simulation results as well as analyzing the simulation scenario of land combat forces operations employing CEC.

Chapter VI concludes the thesis with possible areas for further analysis and research.

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II. EVOLUTION OF NETWORK CENTRIC WARFARE

A. COOPERATIVE ENGAGEMENT CAPABILITY (CEC)

1. Employment of CEC in the USN

CEC has been developed and tested for the USN, by Raytheon, since the 1980s. This capability allows combat systems (essentially Carrier Battle Groups (CBG)) "to share sensor, decision, and engagement data among combatant units without compromising timeliness, volume and accuracy of data" (Hopkins, 1995).

This integration of CEC is primarily used to deter and deny any air threats such as fighters and anti-ship missiles from interrupting naval operations and/or their survival. Other than the physical network of the forces, communication linkages between these forces allows the naval forces to fight as a complete navy combat entity rather than individual land combat sectors (Figure 6). Thus, with CEC these ships in a CBG have gained various advantages, three of which are described as follows.

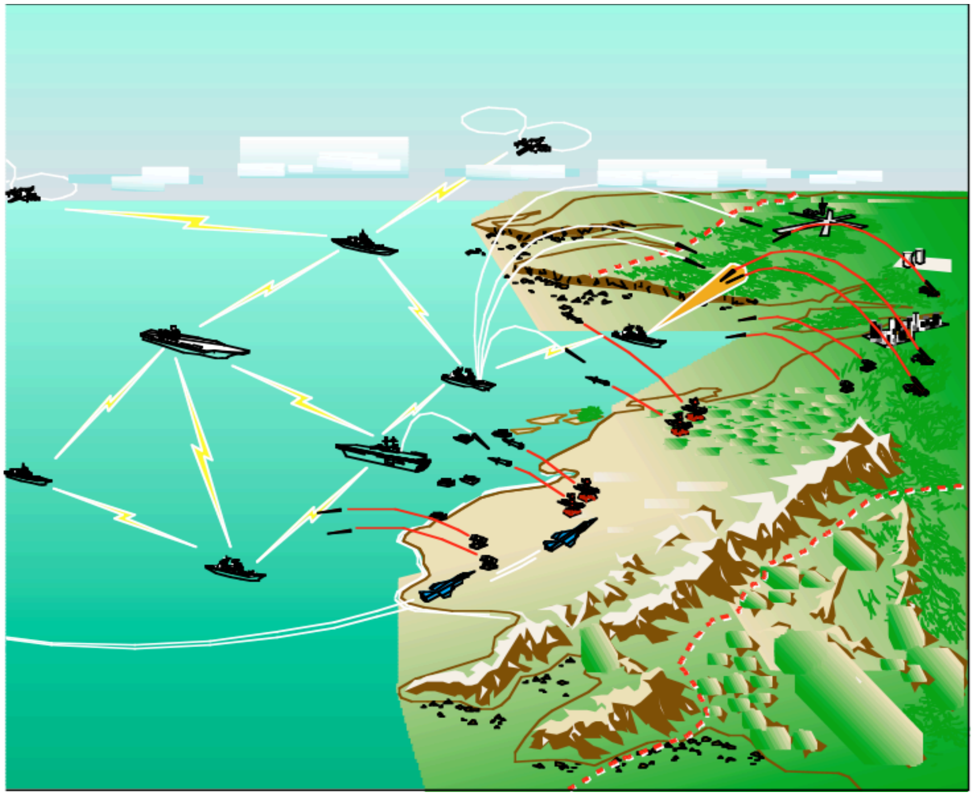

Figure 6. The littoral environment (From: Hopkins, 1995)

2. Capabilities Enhancement by CEC

(1) Higher SA. The navy ships as well as their allies are equipped with 'eyes' over a larger operating area, collecting and sharing vital and time-critical information with one another. By connecting to the sensor resources from land (Firefinder Radar) and air (E-2C Hawkeye), the CBG will be apprised of any potential air threats in their operating environment. They are also able to gain an edge in detection time by focusing their radar beams towards the direction of the potential air threats.

(2) Precise, accurate, and identical pictures of the air threats are derived from sensor data from various nodes of a network-centric engagement. With at least two ships tracking a common air threat, these ships communicate and

share real-time information within the CEC network to 'stitch' up the tracks from various ships and form a comprehensive picture (Figure 7). In the event that a ship is tracking an air threat alone, that ship can initiate a collective scanning, tracking and data enhancement of the threat by sending the threat information to another ship. This initiation is also known as precision cueing (Hopkins, 1995).

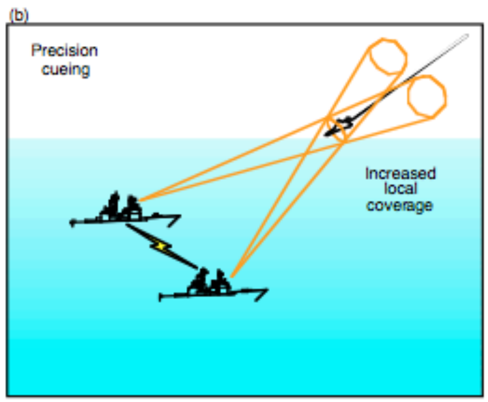

Figure 7. Composite tracking and identification, precision cueing (From: Hopkins, 1995)

(3) Ability to engage a common air threat efficiently and effectively as a group.

With the precise tracks of the air threats, the engagement process for this air threat among the multiple shooters within the CBG allows one primary ship to engage the air threat while other ships maintain their continuous feeding of tracks to the CEC network. Through this networked information distribution, any ship can be commanded via the fleet commander or automatically by the network control unit to engage the air threat without directly tracking the threat. For the network control unit to operate automatically, a set of doctrines is required to be loaded prior to the operation of the CEC. The automated

generation of engagement command reduces the need for every ship to initiate the engagement process and counter the air threats based in every scenario.

However, the real-time CEC process requires fast processing and complex architecture. A snapshot of the CEC functional allocation is shown in Figure 9. There are three subsystems: the (1) Data Distribution System (DDS), which handles the transfer of data through the phased array antenna, (2) Cooperative Engagement Processor, which consists of 30 commercial microprocessors to perform critical functions such as track filtering and sensor interfacing, and (3) modified weapons system, which consists of add-ons to the existing components on-board the ships.

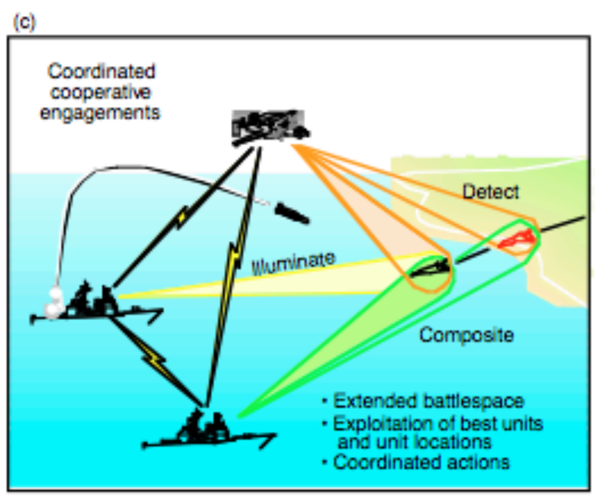

Figure 8. Coordinated cooperative engagements (From: Hopkins, 1995)

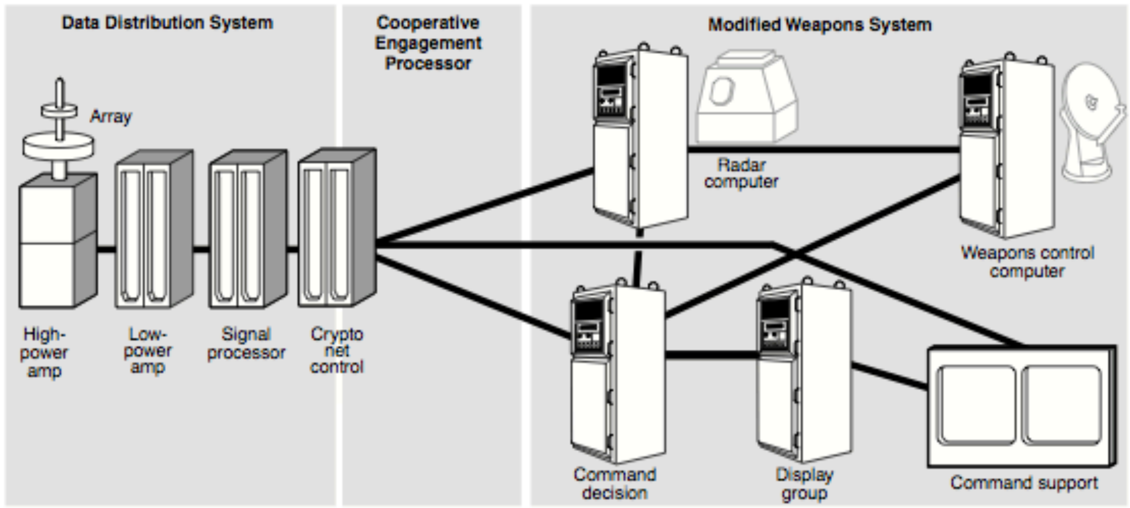

Figure 9. CEC physical components (From: Hopkins, 1995)

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III. STUDY OF CEC ON LAND SYSTEMS

A. LAND SYSTEMS

1. Command and Control (C&C)

NATO defined C&C as Military Function 01: "The organisation, process, procedures and systems necessary to allow timely political and military decision-making and to enable military commanders to direct and control military forces" (NATO, 1996). In addition, a C&C system is defined to include: headquarters facilities, information systems, sensors and warning installations, and communications (NATO, 1998).

C&C is part of a functional decomposition of another function: 'to manage' (Langford, 2012).

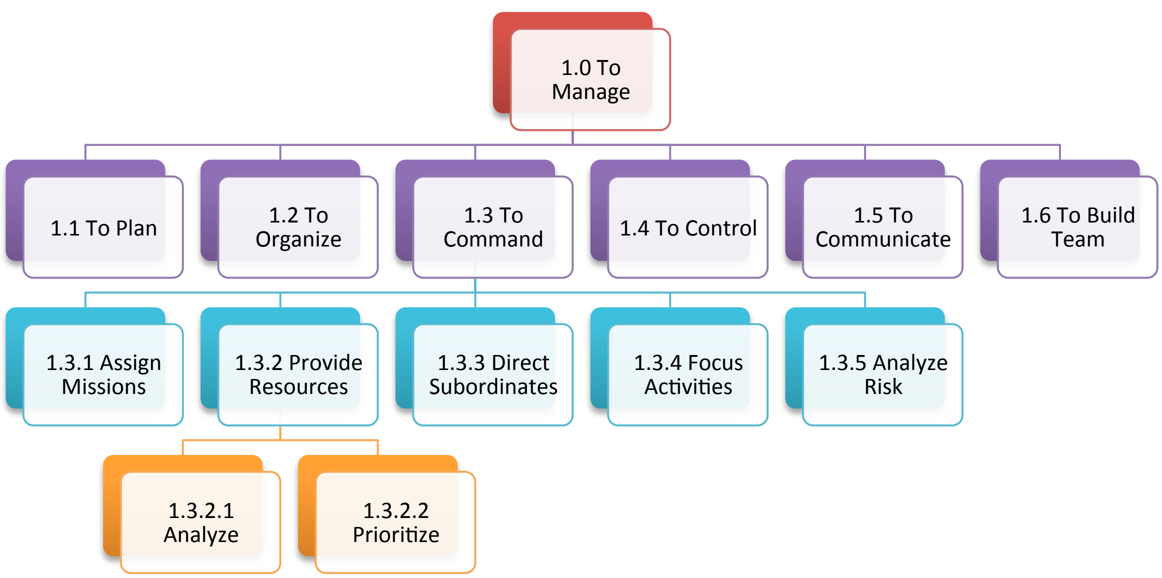

Figure 10. Functional decomposition of the functions 'to manage' and 'to command' (From: Langford, 2012)

Command and control are two separate functions and work alongside other functions such as 'to plan' and 'to

organize'. Managing is akin to leading subjects under one's authority to meet the objective.

> 'To command' is to perform the art of assigning missions; providing resources (analyze, prioritize); directing subordinates (guide, set policy, focus the force to accomplish clear objectives); analyze risk (identify, assess). 'to control' is to define limits; negotiate; deal with constraints; determine requirements; allocate resources; report; maintain performance (monitor, identify, correct deviations from guidance). (Langford, 2012)

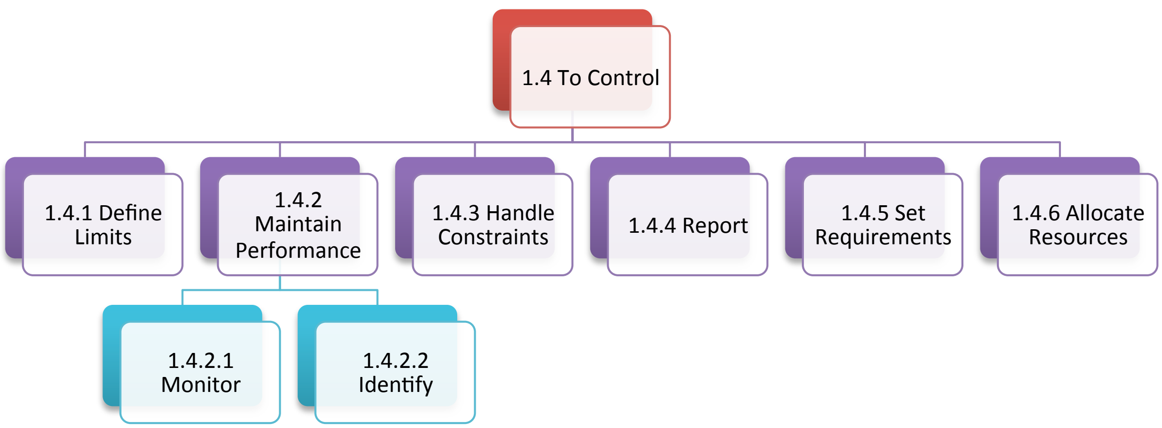

Figure 11. Functional decomposition of 'to control' (From: Langford, 2012)

As can be seen by the functional decomposition, C&C are very different, and often different people perform these two functions. The one that performs 'to command' usually shoulders higher responsibility and authority while everyone along the chain will have to perform 'to control,' whether it is over an individual or others.

2. CEC C&C

The C&C structure in the USN's CEC is rather simplistically complex. Every ship shares the same responsibility of maintaining self-defense, initiating requests and also responding to requests, as well as sharing responsibility in tracking and engaging the targets. As such, the C&C is dynamic and situation-dependent. In terms of engaging the targets, these activities can be coordinated conventionally via command channels or cooperatively via CEC with the activation of a coordination doctrine by the designated Network Control Unit, used to establish a common set of doctrines, for automated engagement recommendations based on force-level engagement calculations.

3. Defense Organization C&C

CEC is used to counter air threats effectively within the USN CBG. CEC also allows optimization of combat powers to extend radar-scanning range, track with higher accuracy and engage targets efficiently. In short, CEC allows the fast sharing of critical information within a group and optimizing this time and information advantage to counter the threats/enemies.

For land systems, one of the operational areas that could employ CEC is the air defense mission, intercepting any incoming projectiles such as rockets, artillery, and mortars. In general, the land air defense mission employs the same CEC concept as the USN CBG: scanning, tracking and engaging air threats. Using the Army C&C system as a reference, an analysis is performed with the design requirements of CEC.

In the U.S. Army C&C system (Figure 12), the pertinent functions that are relevant to CEC are circled in red. The army is constantly collecting and disseminating information throughout the entire command chain regarding the enemy forces and its environment, using Common Operational Picture (COP). The COP builds the Army's SA depending on the information reporting process, information transmission rate and communications security. The operating systems of the army forces must be coherent and interoperable for such information transfer. The details of the orders to be carried out, transmitted to the units tasked with the accomplishment of those orders, is also part of the information transfer, and through the OODA analysis, this relay of details should be performed at the slightest delay to notch time and strategic advantage over the enemy forces.

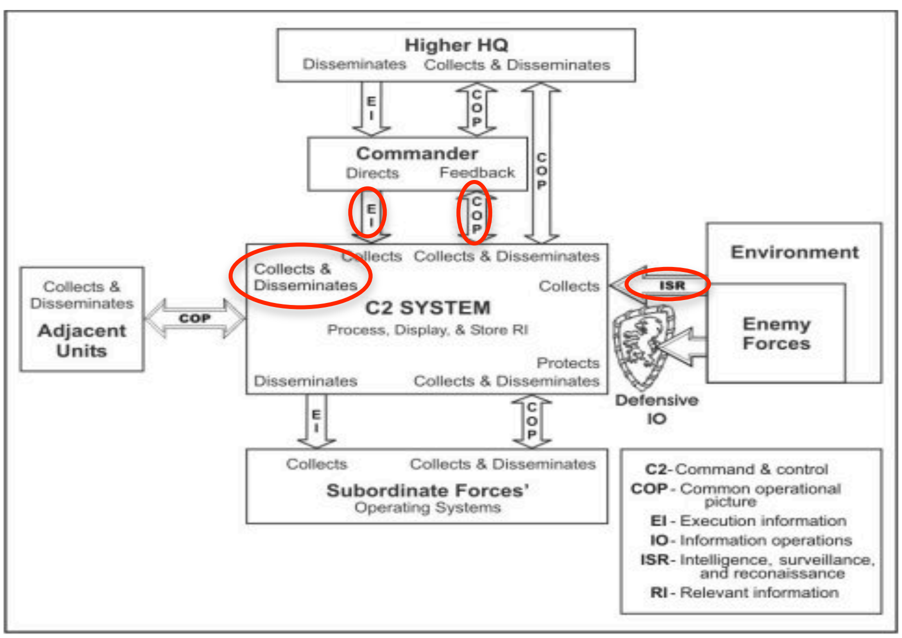

Figure 12. Information and the C&C System (From: Globalsecurity.org, 1997)

Figure 13 shows the mapping of capability needs of the USN CBG to the design of the CEC components. It is always imperative for defense organizations to reduce casualties and fatalities to maintain their combat power against high kill rate through advancement in technology and military tactics. As such, the capability need to achieve the objective of reduced casualties and fatalities is to increase the survivability of the troops through the design requirements of constructing a COP, security in communication network with real-time data communication as well as automated decision making for fast response. Without the design requirements, the capability need would be hard to fulfill and thus, affect the design of the CEC system. The CEC component is designed specifically to perform the requirements stated so as to achieve the capability needs. In the case of the capability need to increase survivability, the CEC components shown in Figure 13 were all designed to perform the requirements as discussed earlier, to increase survivability. The figure also shows other capabilities needs of the USN CBG that map to the design of the CEC components.

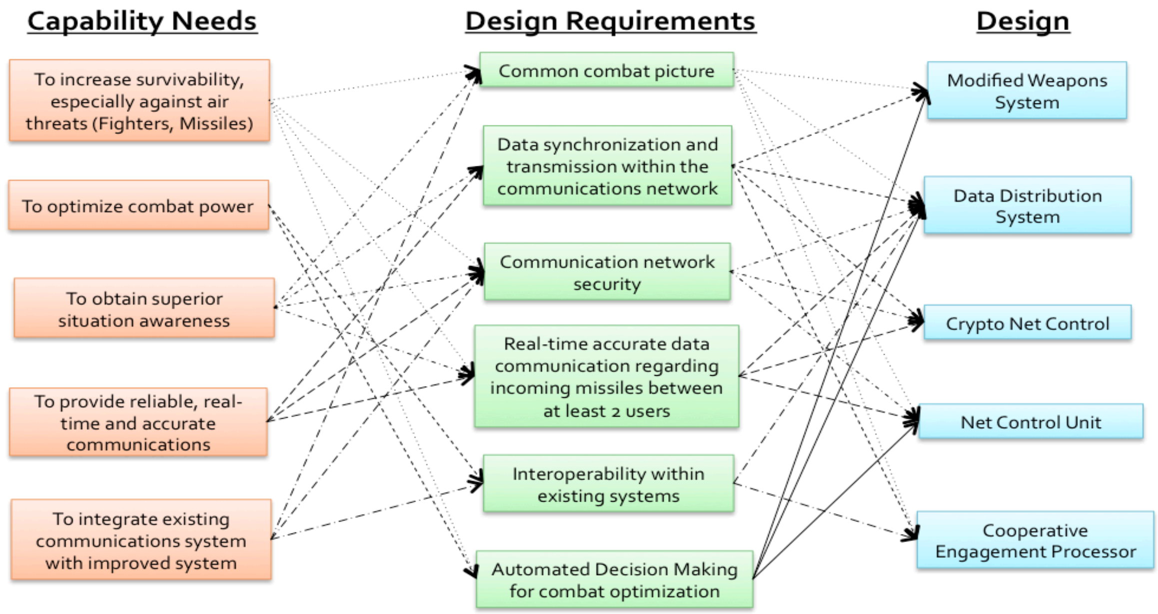

Figure 13. Mapping capability needs to CEC design

Although there are similarities in terms of the design requirements and functions of the Army C&C systems, there are several key differences employed in different operating environments such as sea and land.

B. STUDY OF SEA AND LAND OPERATING ENVIRONMENTS

There are differences operating in the sea and land combat environments. The following segments describe the four key differences: (1) environment, (2) threats, (3) platform, and (4) reaction time to threats in these environments.

1. Environment

In the navy combat environment, there are multiple terrains with which naval combat ships interact. The naval combat forces would need to monitor airspace, sea surface, underwater, and land areas for enemies, intelligence, and SA. Each of these terrains is unique in its environmental

characteristics (e.g., climate, humidity, etc.); as such, each requires various sensors and shooter systems to defend and attack against particular enemies. In the land combat environment, there are thick vegetation and high mountains that obscure vision and communications. At the same time, the enemy is moving, at times hiding to deny detection, and at all times using terrain to gain strategic advantage.

With modernization and urbanization, the land combat environment becomes complex and dynamic with the combat zones shifting into cities, towering with high-rise buildings that further deny vision and communications, widespread use of homes for immediate shelters, covers and traps, underground networks and groups of residents that may or may not be hostile. All these expand the complexity of the land terrain and combat responsibilities.

At sea, it is usually uncommon that an enemy aircraft will have an innocent civilian sitting in the cockpit while the pilot is trying the engage his targets, or civilian ships sailing into the middle of air-sea engagements in combat zones. But in the land combat environment, it is very common for civilians to be situated near the engagement, and some might be deliberate (Calkins & Fisk, 2006). Thus, with the addition of these ambiguous 'new combatants,' the land combat environment is undeniably clouded by a host of unknowns.

2. Threats

The threats that navy ships face are torpedoes, anti-ship ballistic missiles and rockets from various sources. They have long endurance and travel at high speeds that are challenging to intercept. These missiles cause serious

damage to ship’s operations, especially the sophisticated sea-skimming missiles that take advantage of the earth’s spherical nature as well the “sea clutter” that obstructs and disrupts the scanning of such missiles by the ship’s radar. Nonetheless, these anti-ships missiles are usually individually launched (often two due to high per-unit cost) and thus the ships in the USN CBG may be handling small quantities of missiles at a time (Navy.mil, 2009).

The land combat forces face a variety of threats, ranging from bullets and Improvised Explosive Devices (IEDs) to rockets fired from a large variety of platforms such as rifles, attack helicopters, fighter aircraft and indirect weapon systems, in the forms of rockets, artillery shells and mortar bombs. The missiles or bombs released by attack helicopters and fighter aircraft, like the anti-ship missiles, are usually launched in pairs, as these precision munitions require less quantity to destroy their targets. Similarly, rockets are usually armed with a precision module to accurately seek out its target and hence are launched in pairs or individually. However, for other forms of projectiles such as mortar bombs and artillery shells, one can expect about 450 mortar bombs from 120mm mortar tubes to ‘pour down’ onto an area within minutes (FAS.org, 1999).

This is similar to the scene in the movie 300, in which arrows generate an intimidating and terrifying effect by raining down upon a group of warriors, who face the threat with their shields up and bodies down and under (Figure 14).

Figure 14. Raining arrows (From: Snyder, 2007)

In modern wars, such mass firing of projectiles is usually for area targets or stationary targets spread over an area, with or without vegetation and cover. Some examples of key area targets include tank platoons laagering around an enclosed area, C&C headquarters and deployed artillery batteries.

3. Platform

The platforms vary greatly between the sea and land combat environments. At sea, the CBG consists of an aircraft carrier and its escorts such as destroyers to protect the 'mother ship' (Figure 15). Each of these ships has sizeable area for storage and equipment such as radar, weaponry and C&C, allowing them to perform sets of functions such as detection, engagement and commanding of the troops.

Figure 15. Carrier battle group (From: Navsource.org, 2010)

In the case of land combat forces, functions commonly require a smaller platform area to hold the equipment. Thus, it would be costly to develop a single land unit that was big enough to perform multiple functions such as detect, engage and command. These functions would need to be de-centralized due to the lack of platform availability.

For example, the Firefinder weapon locating radar (Figure 16) requires two trucks to deploy. As such, to match the equipment that a ship carries, it would need many more trucks, which tactically creates a large signature in a cramped combat environment.

If there is any additional equipment to be installed or loaded, the common approach by the land forces would be to equip with more vehicles to carry these items; for current ships, mounting could simply be done on certain areas of the ship to accommodate the new items. Furthermore, adjustment can be made for new ships without considering the size of the terrain, while for the vehicles of land forces, dimensions of the platform are critical to ensure that the vehicle is able to overcome difficult

terrain such as steep slopes, fit onto mobile bridges and through mine clearance lanes, etc. Thus, land forces have more difficulty in accommodating new equipment and items than the naval forces.

Figure 16. AN/TPQ37 Firefinder weapon locating radar (From: Radartutorial.eu, 2006)

4. Reaction Time to Threats

Due to the open environment of the sea, the air threats are usually launched at a distance to prevent counter fire. As such, the ship’s reaction time to the air threats is dependent on its radar capabilities such as the radar scanning range and ability to filter sea clutter to detect sea-skimming missile. The longer the range and the more sensitive the radar, the longer the reaction time to counter the air threat effectively.

In the ‘deceptive’ land combat terrain, the air threats, in this case mortar bombs, could be launched from just hundreds of meters, such as M120 120mm mortars, which have a minimum range of 200 meters with the delivery of 60 bombs in 1 minute (FAS.org, 2000). Thus, the reaction time

for the land combat forces is significantly lower than that of the ships. In such instances, radars might not be relevant or useful due to the meager reaction time. Perhaps for longer-range projectiles such as artillery or rockets, more reaction time could be vital for the combat forces' survivability. Nonetheless, the length of the reaction time is dependent on the land forces' radar capability and information transfer rate.

5. Anti-Air Capability

Due to the environment that the naval forces face, these ships are usually equipped with anti-air weaponry, backed by constant research and development to produce better anti-air defense against anti-ship missiles. Each ship in the CBG has at least basic anti-air defense systems such as the Phalanx Close-In Weapon System and Sea Sparrow (Navy.mil, 2012). However, for the land forces, anti-air defense capability tends to reside at brigade level or higher. The anti-air defense platforms, including the weapon-seeking radar, are usually commanded in a centralized role due to scarcity and objective needs of the overall mission. Also, the anti-air defense platforms are used for area protection or specifically to protect important assets. Nonetheless, all troops are trained with techniques, such as using personal firearms against low-flying aircrafts to provide alternate forms of anti-air defense. A summary of the key differences is shown in Table 1.

Table 1. Differences between sea and land combat environment

Characteristics	Sea	Land
Environment	Open with sea clutter	Compact, cluttered with buildings, residents
Common Threats	Long-range sea skimming missiles	Projectiles
Platform	Large platform	Limited capacity
Reaction time to threats	Dependent on radar capabilities	Merger duration
Anti-air capability	Individually equipped	Usually Brigade level or higher

The two operating environments have major differences, with the land forces operating in a decentralized manner with small clusters of units while the naval forces operate as a whole in a decentralized manner.

C. POSSIBLE LAND OPERATIONS EMPLOYING CEC

With the understanding of the capabilities that CEC is able to provide to the naval forces, there are some land operations that could employ CEC.

1. Anti-air Defense Mission

Similar to the USN CBG, the land forces could use CEC's ability to engage a common air threat efficiently and effectively as a group. As discussed, the land forces have limited air-defense capability and are usually deployed to

protect specific assets or conduct area defense. With CEC, the air-defense platforms can be connected to scan further and possibly provide early warning, especially against long-range weapons systems.

Airborne radar platforms (such as the E2C Hawkeye) can be integrated with land forces to provide early warnings on incoming rockets, fighter aircraft, or attack helicopters. This information could allow the forces to initiate their anti-air defense process earlier. Also, better decision could be made to counter these threats. Using the rapid distribution of information, CEC may even overcome the ineffectiveness of early warning against mortars bombs and artillery shells mentioned earlier.

2. Battlefield Monitoring

Other than providing early warning using CEC's ability for the rapid distribution of information, attaining higher SA of the land forces and the current battle in a larger scale could assist commanders to tactically 'shape' the battlefield with higher certainty.

It is always hard to plan anything with unknown status and predicted forecast of the current status. Updates from the battlefield usually arrive through voice communications. Clarity, audibility and accuracy of the information vary in the confused and chaotic environment. In a more modern combat environment, updates come in clusters in a small-scale reporting format and dependent on data communication rate with manual updates on a common operation picture.

Thus, if commanders are able to obtain higher resolution on the details and progress of the overall battles, they can act more decisively and with better appreciation of the battle as it currently stands. Commanders on the ground are also able to appreciate the adjacent battles and make sense of the progress of the overall battles.

Lastly, combining those updates and information into a common operating picture allows the entire chain of forces to 'see' and 'talk' with their forces and allies better. This potentially reduces delay and confusion in execution.

3. Integrated Strike Mission

Using CEC's ability to generate a real-time, precise, accurate and identical picture of the air threats as well as its effectiveness and efficiency in group combat, strike missions (which are usually executed at division (DIV) level or higher) can be orchestrated to support smaller combat units such as battalions or even companies. This concept is part of the Joint Vision 2010 (DOTE&E, 1999) to achieve new levels of effectiveness in joint warfighting (Cohen, 1999).

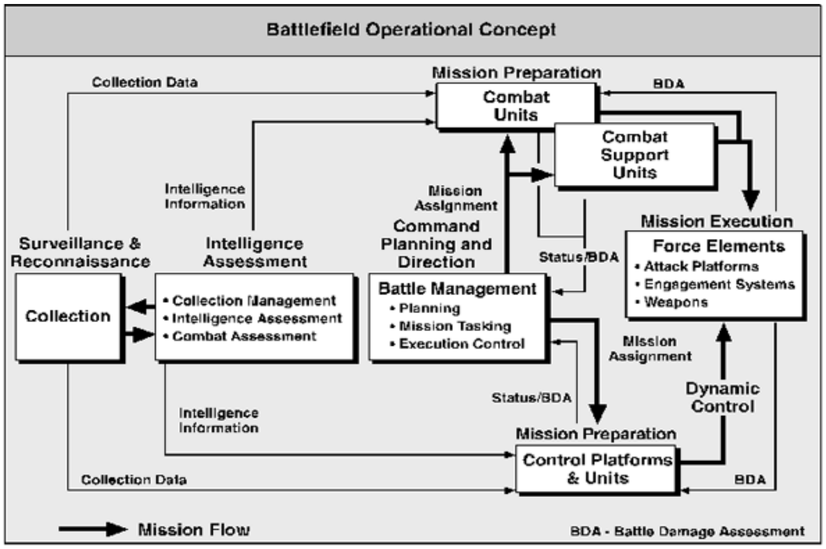

Figure 17. Joint Strike Battlefield operational concept (From: Cohen, 1999)

Integrated Strike missions usually involve air-land platforms, which might not share the same operating picture. As such, useful information such as air threats (fighter aircraft and attack helicopters) may not be shared across these combat services.

From these three land operations, CEC would be more relevant and add higher value to the land anti-air defense capability where there are substantial capability gaps (due to the scarcity of the anti-air systems) to collectively and effectively counter air threats. Also the air threats, especially the projectiles, are deadly and cause potential mission failures.

Figure 18 shows the operational concept employing CEC on the anti-air defense of a DIV battlefield, with three Brigades (BDE) segmented by the blue dotted lines.

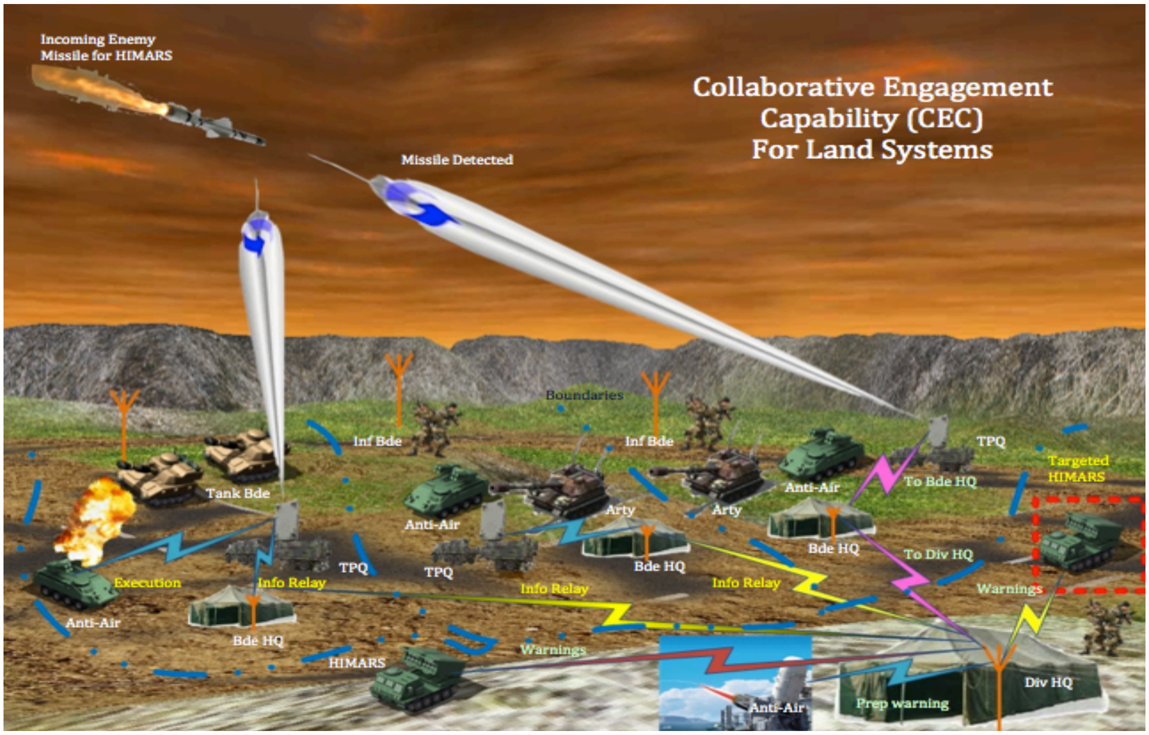

Figure 18. Operational concept for anti-air defense

An incoming enemy missile is detected by one of the BDE Weapon Locating Radar (TPQ). The information regarding this missile is relayed to the BDE Headquarters (HQ), who then relayed the information to the DIV HQ for broadcasting to other BDE HQs as well as relevant units such as the targeted DIV’s High Mobility Artillery Rocket System (HIMARS), which was analyzed by the BDE TPQ. The targeted HIMARS could then execute evasion drills to move out of the impact area. The TPQ and anti-air unit of the leftmost BDE is within range of the enemy incoming missile and thus initiates execution drills with the anti-air rounds to destroy the incoming missiles. The DIV HQ will then prepare its own anti-air unit to destroy the incoming missiles as well as the other HIMARS unit to counter fire on the enemy, if necessary.

With this concept, analysis on the employment of CEC on anti-air defense system is conducted to provide deeper understanding of its feasibility and ability to leverage CEC’s ability to hone land air-defense capability.

IV. SIMULATION METHODOLOGY

A. SIMULATION

In order to test the concept of CEC on land systems, which may require a division's worth of assets, a large amount of cost needs to be budgeted for this logistically, time- and labor-intensive experiment. Thus, a modern, effective and cost-efficient testing method known as Modeling and Simulation (M&S) will be used. M&S is able to provide a better resolution of the model that is tested, conducting more in-depth analysis of the scenarios and thereby producing more accurate results of the simulation.

Other than using M&S, computation methods such as Back of Envelope (BOE) will be used to obtain first cut data of the CEC land systems analysis. This will provide a quick forecast of the possible scenario outcome before a detailed time-based simulation. Design of Experiments (DOE) using the Taguchi method will be used to reduce the combination of parameters executed in ExtendSim for a detailed time-based simulation.

B. MODEL DESIGN

1. Overview

For this analysis, the model will simulate incoming air threats (mortar bombs, artillery shells and rockets) fired at various velocities and ranges with land-based DIV air defense system (TPQ and anti-air weapons) to detect and counter these threats. In the midst of detecting and countering these threats, parameters will be varied during the M&S depending on the results from the BOE. Tentatively,

four parameters will be analyzed to represent the effects of the implementation of CEC into the land systems during the M&S. They are the: (1) rate of information transfer (process time) between the TPQ and anti-air weapon, (2) number of air threats that the anti-air system (one for current system and three for CEC land system) is engaging at one time, (3) detection range, and (4) maximum anti-air engagement range. Lastly, the metrics for this model are the number of air threats that are intercepted as well as those that successfully evaded the anti-air defense system.

2. Assumptions

The following assumptions and initial conditions were used in the simulation:

Table 2. Specification of air threats

Air Threats	Muzzle Velocity (m/s)	Fired Range (km)	Projectiles fired
M120 120mm mortar	315	5.6	60
G5 Artillery	923	10	60
Pinaka Multi Barrel Rocket Launcher	1,600	40	2

The air threats listed in the table above are used due to their common employment by land forces. These air

threats, with the proposed projectiles, are assumed to be capable of destroying a land target.

The air defense system consists of TPQ and anti-air system with the following specifications:

- TPQ: The TPQ is assumed to have a detection range of 40km with apogee ratio of 0.4.
- Anti-air system: The anti-air system is assumed to have a rate of fire of 60 rounds per second, muzzle velocity of 1,110 meters per second, probability of intercept of 0.2, maximum and minimum engagement range of 10 kilometers and 500 meters, respectively.
- The rate of information transfer between the TPQ and anti-air system will be termed as process time in this simulation, with a default time of 4 seconds.

The values of the parameters above are defined as the default values of the M&S model.

C. SIMULATION TOOLS

1. BOE

Using Excel as the platform to conduct BOE, mathematical computation using the parameters listed in the earlier assumptions allows the first cut data to be obtained. In order to compute the metrics, there are five parameters to be calculated: (1) duration before impact, (2) duration from detect to impact, (3) duration from engagement to impact, (4) duration of engagement and lastly, (5) total anti-air munitions. The formulas as well as a snapshot of the BOE model are listed in the Appendix.

The result from the computation of the anti-air munitions will be used in the computation of the metrics. With the probability of intercepting of the incoming air

threats by the anti-air munitions, CRITBINOM function[1] will be used to examine the number of intercepted incoming air threats with each anti-air munition as an independent Bernoulli trial.

To extend the computation results, data are tabulated to analyze the effects of maximum anti-air engagement range as well as process time on the number of un-intercepted incoming air threats. The results in the data table are calculated and averaged through 10,000 runs.

2. DOE

DOE using Taguchi method was conducted during the ExtendSim simulation to identify the parameters that will have the greatest impact on the effectiveness of the air-defense capability. The parameters that are relevant to CEC land system and are tested are **dependent** on results of the BOE.

The Taguchi method can efficiently conduct experiments through calculation of combinations of certain value levels of parameters, instead of executing every possible combination during the simulation, which can be time consuming. A simulation with four control variables with four levels would take 4^4 or 256 combinations but using Taguchi methodology, it would take just 16 combinations.

[1] The CRITBINOM(n, p, alpha) function examines for various x the cumulative probability of x successes in n independent Bernoulli trials. Each trial has the associated probability p of success. CRITBINOM returns the smallest value of x for which this cumulative probability is greater than or equal to alpha.

3. ExtendSim

The model shown in Figure 19 will be used for the M&S to simulate the CEC land system's operational environment. For the first three simulation runs, a baseline model with the default parameters values listed in Chapter IV, Section B2 will be simulated. Each simulation run consists of 100 trials, taking the average as the final results. For the subsequent simulation runs, the parameters will be based on values obtained from DOE.

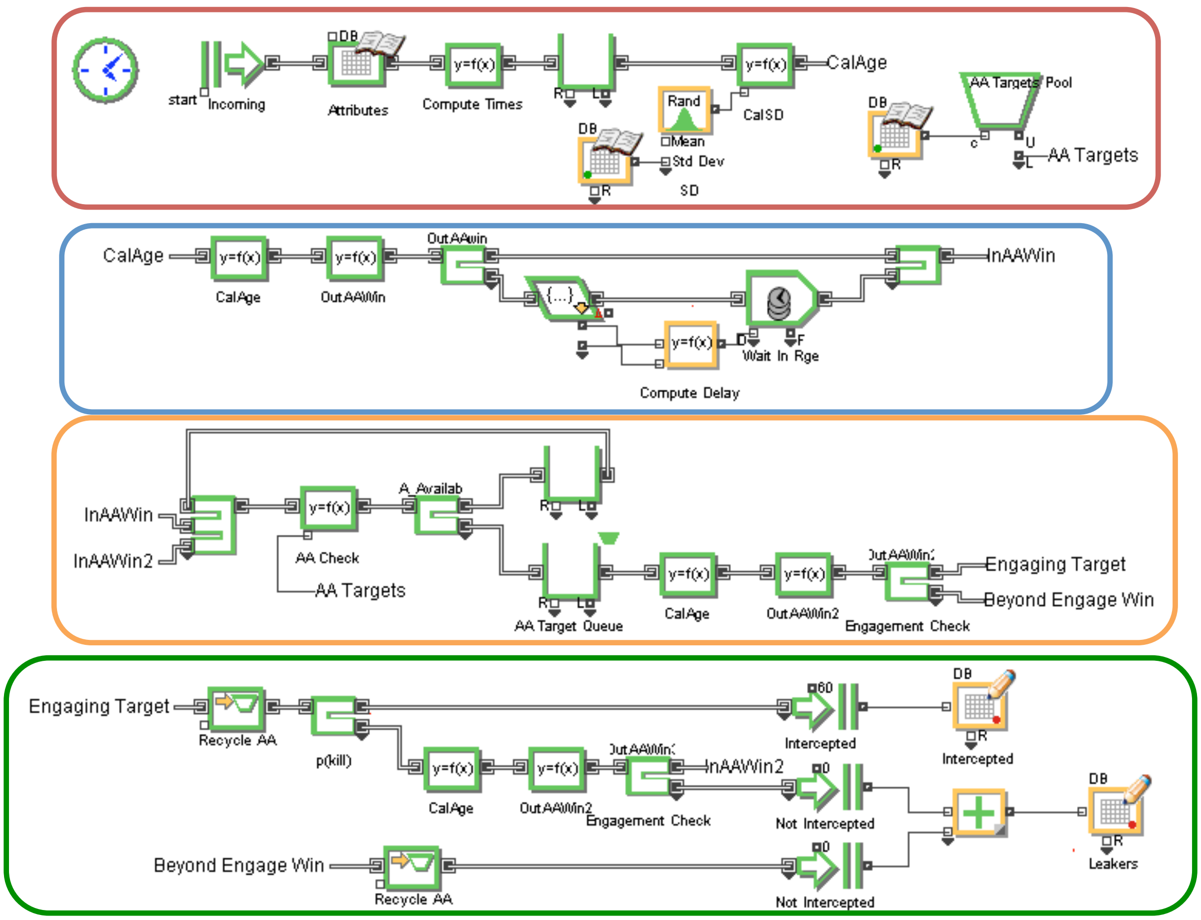

Figure 19. ExtendSim model

The model comprises four parts, sequentially from top to bottom in Figure 19: (1) initialization of data (red box), (2) computation to ensure incoming air threats are within anti-air engagement window (blue box), (3) computation on whether the incoming air threats are engaged, leaked due to insufficient anti-air weapons, passing of the engagement window or simply inability to intercept the incoming air threats (orange box), and lastly (4) consolidation of the data (green box).

For the initialization of the incoming air threats, the rate of fire varies due to different firing rates by different weapon. Also, it is assumed that the firing of the incoming threats would display a normal distribution with the mean and standard deviation (SD), as shown in Table 3.

Table 3. Values used for ExtendSim M&S

Incoming Threats	Firing Rate Per Firing Unit	M&S for air threats	Mean, SD (seconds)
Mortar Bomb	16rds/min	4rds/4sec	0, 1
Artillery Shell	3rds/min	6rds/20sec	0, 2
Rockets	12rds/30sec	2rds/sec	0, 0

Process time and detection range are computed within the blue box, while concurrent anti-air targets and maximum anti-air engagement range are computed within the orange box. The database in the model captures all the parameters to be tested as well as the results that were to be analyzed.

V. SIMULATION RESULTS AND ANALYSIS

A. BOE

The BOE is computed with the default values listed in Table 3 for the three different incoming air threats, with the results consolidated in Table 4.

Table 4. Summary of BOE results using default values

Air Threats	Fired Range	Incoming Quantity	Anti-air Munitions	Intercepted	Leakers
Mortar Bombs	5.6km	60	160	30	30
Artillery Shells	10km	60	0	0	60
Rockets	40km	2	108	2	0

Through the summarized results, it can be seen that the implementation of CEC would be more effective in anti-air defense systems against artillery shells and mortar bombs. The default values for the anti-air defense system against rockets generate an ideal result with 100% interception of the air threat.

The following segments cover the BOE experimentation and results in detail for each type of air threat.

1. Mortar Bombs

Figure 19 shows the range trajectory of the incoming mortar shells on the target. It is noted that the anti-air system has a short engagement window of about 3.11 seconds.

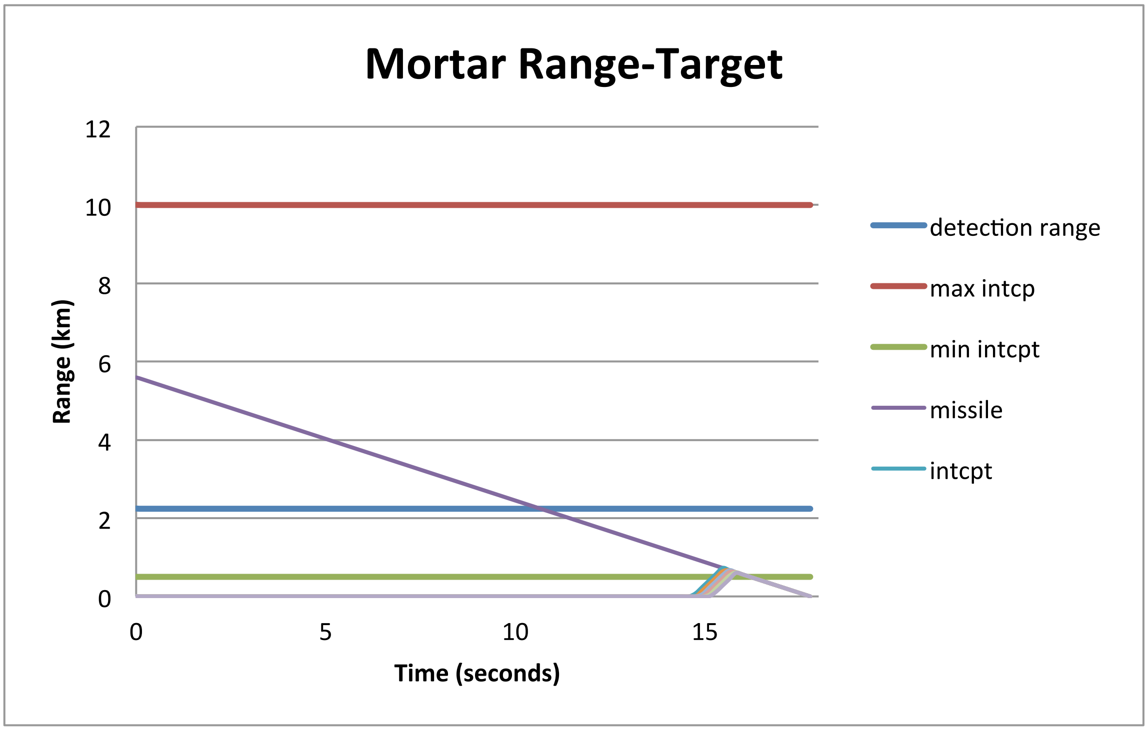

Figure 20. Range target for incoming mortar bombs

Within 17.78 seconds, during which 60 mortar bombs will land on the target, a total of 160 anti-air munitions are expected to intercept these incoming air threats. With the intercept probability of 0.2 and a ratio of about three anti-air munitions to one incoming mortar bomb, about 30 of the 60 mortar bombs are expected to leak through the air defense system.

With various process time and maximum effective range of the anti-air weapons, the values of leakers shown in

Table 5 are obtained and averaged from 10,000 runs. From the data table, process time has more influence on the number of leakers than the engagement range. It can be seen that if the process time is greater than 6.5 seconds, all of the 60 mortar bombs will leak past the air-defense system regardless of the engagement range of the anti-air weapon. This is due to the short engagement window that the anti-air weapon would have from the short engagement range of the mortar. However, it is also noted that with a configuration of process time and maximum effective engagement range of 0.5 seconds and at least 2.5km, respectively, or 1 second and at least 4.0km, respectively, a 100% interception of the 60 artillery shells can be achieved.

Table 5. Effects of process time and maximum effective anti-air engagement range on mortar bombs leakers

		Process Time (s)													
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Max Engagement Range (km)	1.0	33	39	45	51	57	60	60	60	60	60	60	60	60	60
	1.5	14	20	27	32	38	44	50	56	60	60	60	60	60	60
	2.0	1	3	8	14	19	25	31	37	43	49	55	60	60	60
	2.5	0	1	2	5	10	16	22	28	34	40	46	52	58	60
	3.0	0	1	2	5	10	16	22	28	34	40	46	52	58	60
	3.5	0	1	2	5	10	16	22	28	34	40	46	52	58	60
	4.0	0	0	2	5	10	16	22	28	34	40	46	52	58	60

2. Artillery Shells

From Figure 21, there is almost a nil anti-air engagement window due to the fast velocity of the incoming air threats.

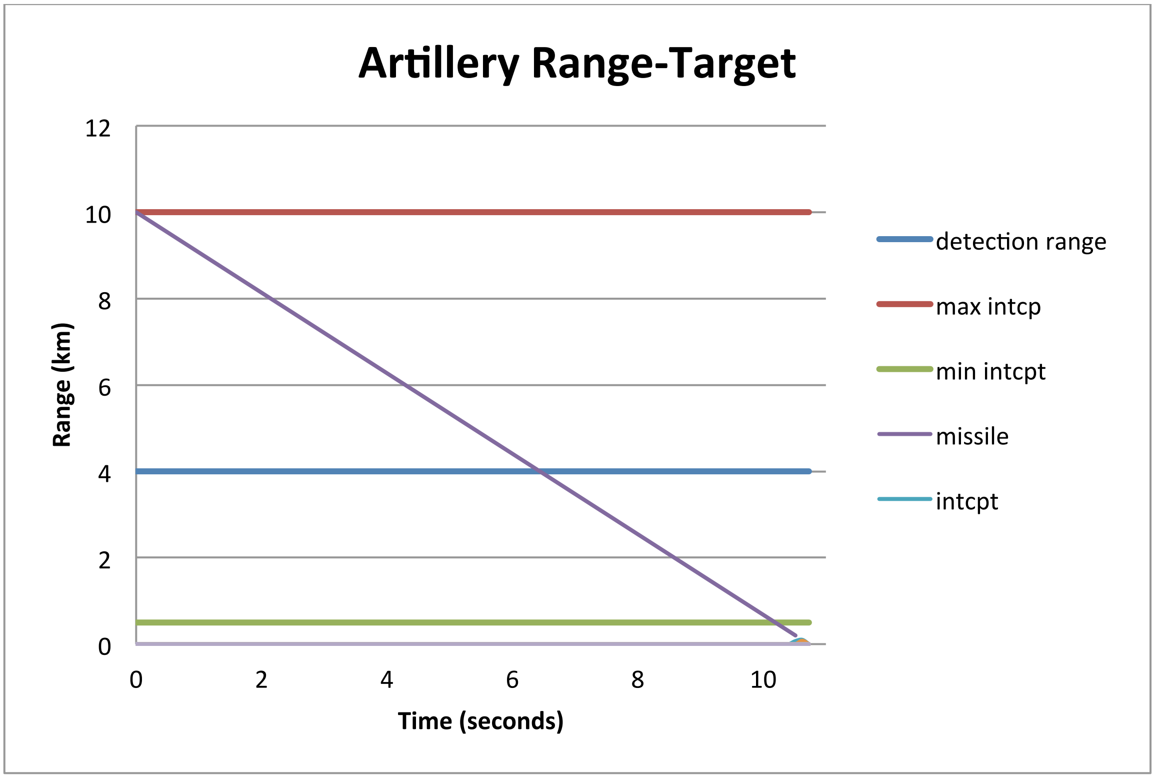

Figure 21. Range target for incoming artillery shells

Thus, at the current fired range of 10km and with almost no anti-air munitions to intercept the incoming artillery shells, the anti-air defense system is ineffective at such ranges or shorter.

With the formulation of the data in Table 6, it is noted that the process time has a close relationship with maximum effective range up to 3.5 seconds and 4km, respectively. Beyond this combination, all of the 60 artillery shells will leak past the anti-air defense system. However, even with a process time of 0.5 seconds and a maximum engagement range of 4km or more, the anti-air defense system could only manage to intercept at most 66.6% or 40 of the 60 of the incoming artillery shells, due to the fast muzzle velocity of those shells.

Table 6. Effects of process time and maximum effective anti-air engagement range on artillery shells leakers

		Process Time (s)							
		0.5	1	1.5	2	2.5	3	3.5	4
Max Engagement Range (km)	1	59	60	60	60	60	60	60	60
	1.5	52	58	60	60	60	60	60	60
	2	46	52	58	60	60	60	60	60
	2.5	39	45	51	57	60	60	60	60
	3	33	39	45	51	57	60	60	60
	3.5	26	32	38	44	50	56	60	60
	4	20	26	32	38	44	50	56	60
	4.5	20	26	32	38	44	50	56	60

3. Rockets

As shown in Figure 22, the air-defense system is able to detect the incoming rockets 10 seconds before a target is hit. However, due to the limited anti-air engagement range of 10km, the engagement window is limited to 1.8 seconds.

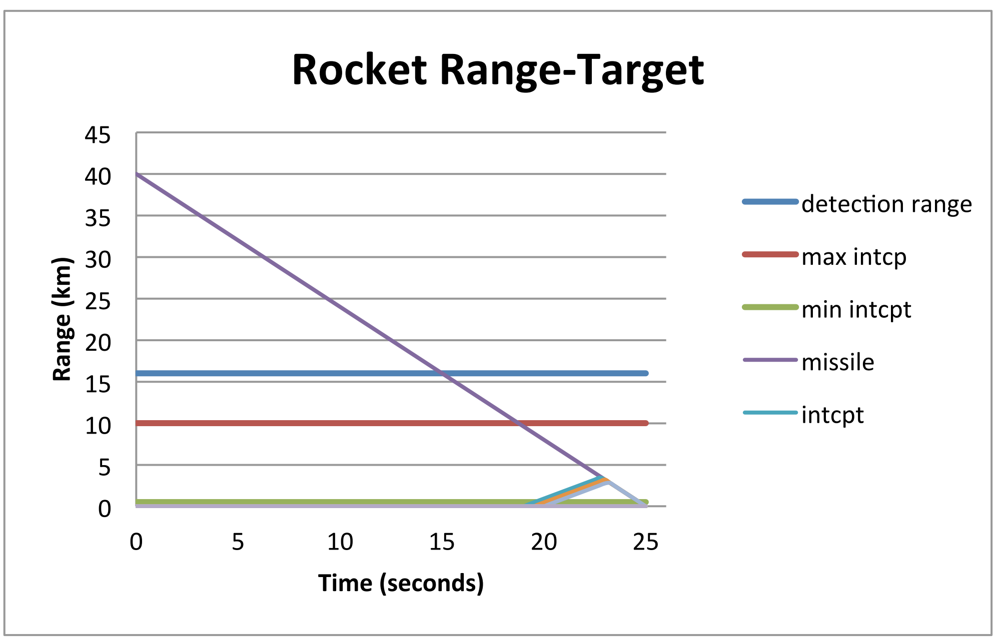

Figure 22. Range target for incoming rockets

With the engagement window, a total of 108 anti-air munitions are computed to successfully engage the two incoming rockets. The success engagement is due to the large number of trials (anti-air munitions) against the low number of air threats (two rockets) or a ratio of 54:1.

With the formulation of Table 7, it is noted that both process time and maximum engagement range up to 9.5 seconds and 16km, respectively, have strong relationship to the number of rocket leakers. With the existing assumption of 10km of maximum engagement range, the anti-air defense system is able to accommodate a less stringent process time of 5 seconds to achieve a 100% interception of the two incoming rockets.

Table 7. Effects of process time and maximum effective anti-air engagement range on rockets leakers

		Process Time (s)																			
		0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
Max Engagement Range (km)	1.0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	1.5	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	2.0	0.1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	2.5	0	0.9	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	3.0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	3.5	0	0	0.2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	4.0	0	0	0	1.6	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	4.5	0	0	0	0.1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	5.0	0	0	0	0	0.5	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	5.5	0	0	0	0	0.0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	6.0	0	0	0	0	0	0.1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	6.5	0	0	0	0	0	0	0.9	2	2	2	2	2	2	2	2	2	2	2	2	2
	7.0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2
	7.5	0	0	0	0	0	0	0	0.2	2	2	2	2	2	2	2	2	2	2	2	2
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	10.0	0	0	0	0	0	0	0	0	0	0	0.1	2	2	2	2	2	2	2	2	2
	10.5	0	0	0	0	0	0	0	0	0	0	0	0.9	2	2	2	2	2	2	2	2
	11.0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2
	11.5	0	0	0	0	0	0	0	0	0	0	0	0	0.2	2	2	2	2	2	2	2
	12.0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.6	2	2	2	2	2	2
	12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	2	2	2	2	2	2
	13.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	2	2	2	2	2
	13.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2
	14.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	2	2	2	2
	14.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	2	2	2
	15.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2
	15.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	2	2
	16.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.6	2
	16.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.6	2

4. Effects of Process Time and Fired Range

In another BOE computation, it is noted that the duration of the process time as well as the fired range of the air threats affects the anti-air engagement window of air-defense window.

With a minimum process time of 10.5 seconds and 6 seconds for intercepting 60 artillery shells and two rockets, respectively, from any range, the anti-air defense system will be rendered ineffective due to the long duration of process time. For process time below the values shown in Table 8, the number of intercepted air threats will be dependent on the fired range; however, the values must be beyond 0.5km, 1.5km and 2.5km for mortar bombs, artillery shells and rockets, respectively.

Table 8. Effects of process time and fired range of air threats on anti-air defense system

Air Threats	Fired Range (km)	Process Time (s)
Mortar Bombs	0.5	-
Artillery Shells	-	10.5
Rockets	-	6

However, for the interception of all the 60 mortar bombs, the values of fired range and process time that will render the anti-air system ineffective varies and it is only at a fired range of 0.5km (regardless of the process time) that the anti-air defense system will be rendered ineffective due to a short detection window.

B. DOE

Through the results of the BOE, it is concluded that (1) fired range of the air threats, (2) maximum engagement range, and (3) process time have great impact on the number of incoming air threats that will penetrate the air defense. In addition to testing of the CEC implementation on land systems, the (4) number of concurrent air targets that the anti-air weapon system can engage at any time is also considered to be relevant for the DOE.

However, it is also noted that through these BOE results, rockets will not be tested in the M&S (except using default values), due to the unlikelihood in combat operations that the quantity, fired range of the rocket and maximum anti-air engagement range would be more than 2, less than 40km, and less than 16km, respectively for a land target. Also, although the detection range tested during the BOE is larger than the fired range of the incoming air threats, except rockets, this parameter will be tested in the M&S as part of the CEC employment.

1. Taguchi Design

Based on the results of the BOE, a DOE (with four factors, four levels, and two noise factors) is computed for various values of the parameters to be simulated. The values of the four levels of each control variable are listed in Table 9.

Table 9. Four level values of the control parameters for DOE

Level	1	2	3	4	Remarks
Detection Range (km)	10	20	40	60	It is assumed that the maximum detection range could be increased to 60km through CEC
Maximum Engagement Range (km)	5	10	20	40	It is assumed that the maximum engagement range could be increased to 40km through CEC
Process Time (s)	1	4	7	10	Process Time of 1 sec assumes almost instantaneous information transfer through CEC
Concurrent Anti-air Targets	1	3	6	9	It is assumed that there could be nine anti-air targets that could be engaged through CEC

The values of the higher and lower limits are estimated to be possible through the implementation of CEC. As such, the maximum engagement range of the anti-air system is assumed to increase to 40km as each of the DIV anti-air weapons is integrated with one another. With these values of the four levels of the control parameters formed, the values of these parameters used in the reduced simulation runs can be generated through Taguchi DOE, as shown in Table 10.

Table 10. Taguchi four control factors four levels design

	Control Factors			
Runs	Detection Range (km)	Max Engagement Range (km)	Process Time (s)	Concurrent Anti-air Targets
1	10	5	1	1
2	10	10	4	3
3	10	20	7	6
4	10	40	10	9
5	20	5	4	6
6	20	10	1	9
7	20	20	10	1
8	20	40	7	3
9	40	5	7	9
10	40	10	10	6
11	40	20	1	3
12	40	40	4	1
13	60	5	10	3
14	60	10	7	1
15	60	20	4	9
16	60	40	1	6

Also, two noise factors and two levels are also tabulated to simulate the possible fired range and rate of fire of the mortar bombs and artillery shells (Table 11).

Table 11. Taguchi two noise factors two levels design

	Noise Factors	
Response Variables	Fired Range (km) (Mortar/Artillery)	Rate of Fire (Mortar/Artillery)
Y1	1/5	(4rds/4sec)/(6rds/20sec)
Y2	1/5	(4rds/2sec)/(6rds/10sec)
Y3	2.5/10	(4rds/4sec)/(6rds/20sec)
Y4	2.5/10	(4rds/2sec)/(6rds/10sec)
Y5	4/15	(4rds/4sec)/(6rds/20sec)
Y6	4/15	(4rds/2sec)/(6rds/10sec)
Y7	6/20	(4rds/4sec)/(6rds/20sec)
Y8	6/20	(4rds/2sec)/(6rds/10sec)
Y9	7.5/40	(4rds/4sec)/(6rds/20sec)
Y10	7.5/40	(4rds/2sec)/(6rds/10sec)

With 10 permutations from the two noise factors two level Taguchi design, a total of 160 simulation runs each for the mortar bombs and artillery shells were performed in ExtendSim to provide statistical analysis on the anti-air defense system.

C. EXTENDSIM

Results from M&S using the default values for the anti-air defense system against the incoming air threats are shown in Table 12.

Table 12. M&S results using default values

Air Threats	Intercepted	Leakers
Mortar Bombs from 5.6km	60	0
Artillery Shells from 15km	8	52
Rockets from 40km	2	0

Interestingly, the M&S results shown that mortar bombs were all intercepted, whereas the interception result of the rockets was expected based on BOE. The number of artillery shells intercepted was increased slightly, compared to the BOE results where there was nil interception. This increase was due to the intervals (normal distribution) of the incoming artillery shells.

D. ANALYSIS OF TAGUCHI DESIGN

With the ExtendSim results from the 160 simulation runs each for mortar bombs and artillery shells, Taguchi analysis using Minitab was performed to provide more insights on the effects of the control and noise parameters.

1. Mortar Bombs

From the Taguchi analysis, rankings of the influence of the control variables on the number of intercepted

mortar bombs was generated. Process time was the most influential control variable, followed by maximum engagement range, detection range and, lastly, number of concurrent air targets.

From the mean plot of the intercepted mortar bombs shown in Figure 23, it can be seen that lower process time increases the number of mortar bombs intercepted. However, there are no changes to the interception of the mortar bombs by the other three parameters: (1) detection range, (2) maximum engagement range, and (3) concurrent air target.

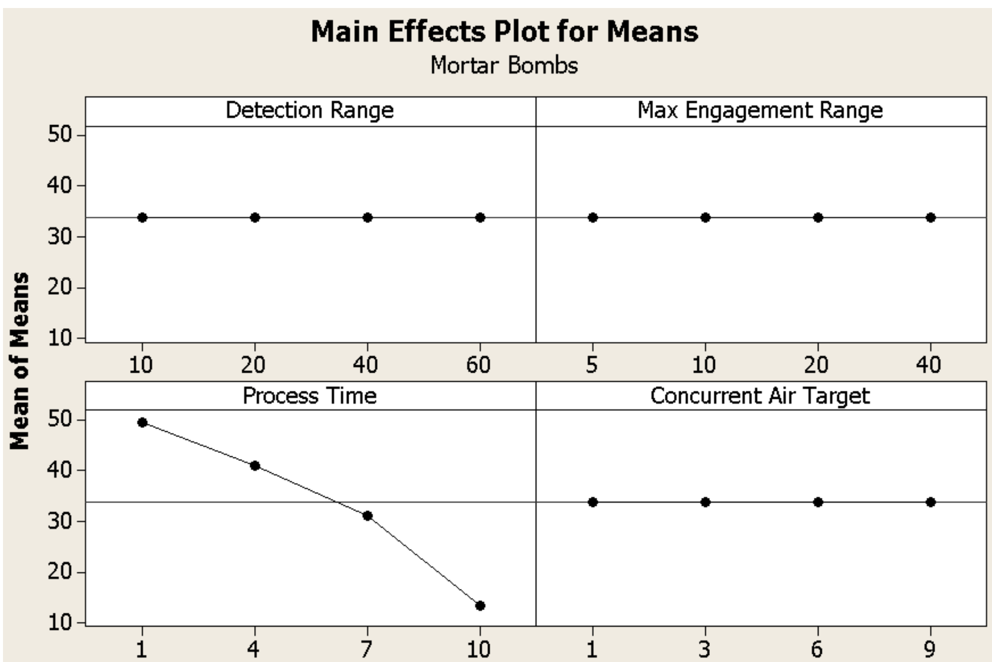

Figure 23. Mean of mortar bombs intercepted

From the Signal to Noise (S/N) ratio plot shown in Figure 24, it can be seen that a process time of 10 seconds has a high S/N. However, based on the mean plot in Figure 23, it would result in a decrease of intercepted mortar

bombs. Similar to the analysis of the mean, the remaining three control variables have insignificant influence on the number of intercepted mortar bombs. As such, the ideal setting to achieve the highest number of intercepted mortar bombs is a process time of 1 second with any other combination of the remaining three control variables. It was predicted using Taguchi analysis that this configuration would intercept about 50 mortar bombs.

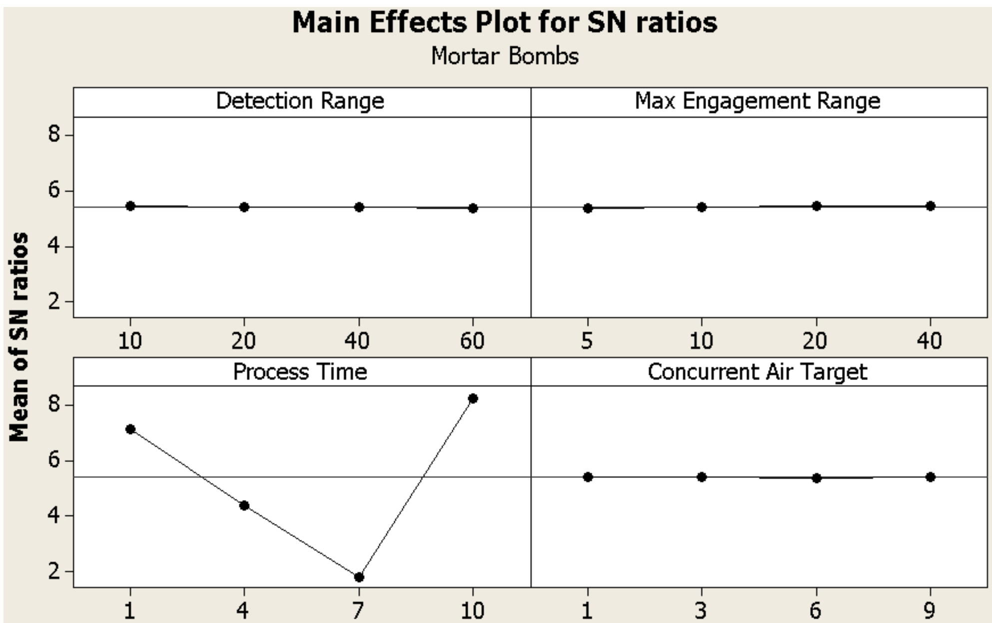

Figure 24. S/N Ratio of mortar bombs intercepted

2. Artillery Shells

From the Taguchi analysis, rankings of the influence of the control variables on the number of intercepted artillery shells were generated. Process time was the most influential control variable, followed by number of concurrent air targets, maximum engagement range and, lastly, detection range.

From the M&S results (Figure 25), it can be seen that the process time is the most significant factor to influence the number of intercepted artillery shells. Despite the minor fluctuation on the number of intercepted artillery shells for the remaining three control variables, there are some observations that are distinctive from the mean plot. It is seen that a detection range beyond 40km does not affect the number of intercepted artillery shells as the maximum fired range of the artillery shells simulated was 40km. The maximum engagement range of 5km and 40km as well as the capability to engage nine concurrent targets yield the highest number of intercepted artillery shells within their respective parameters.

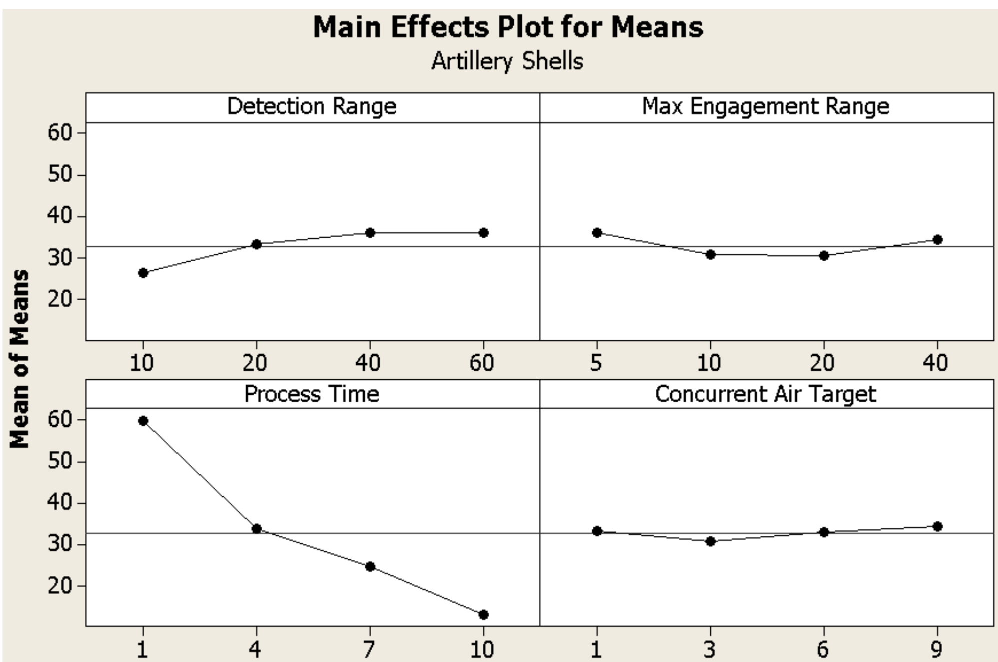

Figure 25. Mean of artillery shells intercepted

The S/N ratio plot shown in Figure 26 clearly indicates that process time of 1 second is the ideal and

influential value to increase the number of intercepted artillery rounds. Thus, the ideal setting to achieve the highest number of intercepted mortar bombs is to use a process time of 1 second with 40km detection range, 5km engagement range and capability to engage nine concurrent air targets. It was predicted using Taguchi analysis that this configuration would intercept about 67 artillery shells. However, as the maximum number of artillery shells tested was 60, it is noted that the predicted value of 67 artillery shells is the maximum number of intercepted shells for the configuration used for prediction.

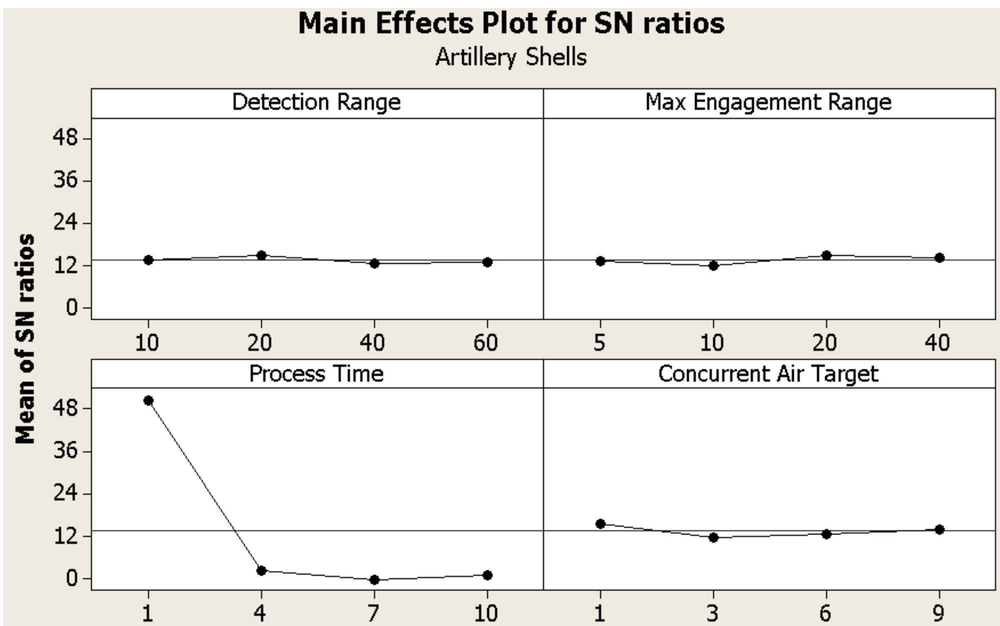

Figure 26. S/N ratio of artillery shells intercepted

E. SUMMARY OF RESULTS

From the simulation results, it is noted that process time is key to the success rate of intercepting incoming air threats. However, process time refers to the rate of information transfer (process time) between the TPQ and

anti-air weapon. This includes the data processing at the TPQ, analysis by the TPQ commander, data transfer (either wired or wireless) between the TPQ and anti-air weapon, decision making by the DIV/BDE commander and execution by the anti-air weapon commander. The process time utilized by these various commanders includes the decision time, dead time, time constant and information delay time. Thus, the process time of 1 second to accomplish these tasks would seem infeasible but, perhaps, the process time of 1 second could be achieved through automation, including the decision-making process of the TPQ commander, DIV/BDE commander and anti-air weapon commander.

Other factors such as detection range, maximum engagement range and number of concurrent targets to be engaged were determined to have little influence on the interception rate of the incoming air threats. Nonetheless, the interception rate of the incoming air threats is also highly dependent on the rate of fire and range of the air threats. In this M&S simulation, the rate of fire (one of the noise factors) is limited to two levels, with the quantity of the air threats fixed at 60 rounds. As such, the anti-air defense system is technically engaging two incoming air threats per second, which provides substantial engagement window for a successful interception based on the rate of fire of the anti-air defense weapon. Unlike the BOE computation, all of the 60 incoming air threats (for mortar bombs and artillery shells) are computed to be engaged by the anti-air weapon in a single salvo, which may or may not be realistic due to the scale of resources that are to be committed and the returns by destroying the target.

Nonetheless, it can be concluded that the interception rate of rockets is high due to the long firing range, which increases the anti-air engagement window and small quantity of the rockets fired upon a target. Air threats from artillery and mortar fire pose potential threats to the land targets and limit the anti-air engagement window. Mortar bombs are observed to be the most dangerous threat through the Taguchi analysis, as it was predicted that the maximum mortar bombs intercepted is 50 out of 60 or 83% of mortar bombs.

VI. CONCLUSION

A. BENEFITS OF CEC FOR LAND COMBAT FORCES

Through the M&S results, land combat forces employing CEC could achieve a higher interception rate of air threats during anti-air defense operations. It was observed that process time is the key factor to increase interception rate of incoming air threats. Real-time information transfers and establishing common combat picture, which are benefits of CEC, could potentially reduce process time.

However, not all of the capabilities of CEC are relevant and useful for the land combat forces. Increasing track accuracy may not be beneficial to the land combat forces due to time taken to track a common target within a short anti-air engagement window and also the high ratio of anti-air munitions against the air threats. Due to the range of the incoming air threats, there are no additional benefits to pooling radar resources in order to extend detection coverage, thus reducing the need to pool the radar resources.

Consideration of the number of air threats as well as the concurrent air threats that are being tracked and engaged must further be analyzed due to the possibility of large quantities of cheap munitions firing on a land target. With multiple threats within a short time frame (such as 60 air threats, in this case), a CEC network would be highly utilized with a large flow of data traffic within seconds in order to share threat data and information, potentially resulting in bandwidth scarcity. Thus, with the

initialization and utilization of the CEC network control unit, the process time could be reduced drastically.

Reducing OODA loop delays such as decision time, dead time, time constant and information delay time would also help in reducing process time. With more stakeholders within the anti-air defense system, establishing preplanned engagement authorization and doctrines could potentially shorten OODA loop delays, thus further narrowing the areas to conduct optimization research and analysis.

Therefore, land combat forces can employ CEC to increase SA among the troops, increase interception rate and reduce process time. However, the implementation of CEC on land systems cannot be taken wholesale from the CEC structure used in the USN, due to the differences in threats, nature of operations, platforms and cost of CEC equipment and implementation. Thus, it is recommended to implement relevant functions of CEC by focusing on improvising the network connectivity structure and rapid data processing rate of CEC to suit the needs of the land combat forces. The needs of the land combat forces include the reduction of process time, increased interception rate of the incoming air threats and, lastly, reduction of cost. Exploration on doctrinal changes to reduce OODA loop delay time should also be analyzed further.

B. FUTURE RESEARCH RECOMMENDATIONS

Due to the scope of this thesis, a number of applicable areas in which further research and analysis are recommended are listed below.

1) Determine the maximum allowable process time utilized by each of the stakeholders in the anti-air defense system to achieve optimal interception rate.

2) Conduct more in-depth analysis of the incoming air threats on various land targets with characteristics such as radar cross section, quantity, area and probability of kill for each target to determine the Returns of Investment in terms of survivability.

3) Apply the concept of CEC on large-scale combat systems such as air-land strike integration and determine the effectiveness against current methodology.

4) Conduct analysis to achieve the capability of CEC on land combat systems with minimum cost.

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APPENDIX

Duration before impact = Fired range/Incoming threat muzzle velocity

Duration from detect to impact = Minimum(Radar detection range*Apogee)/Incoming threat muzzle velocity, Fired range*Apogee/Incoming threat muzzle velocity)

Duration from engagement to Impact = Minimum(Max effective anti-air engagement range/Incoming threat muzzle velocity – process time, Duration from detect to impact – process time)

Duration of engagement = Duration from engagement to impact – (Min effective anti-air engagement range/anti-air muzzle velocity)

Total anti-air munitions = duration of engagement * anti-air fire rate

Intercepted = Minimum(No of inbound, Critbinom(total anti-air munitions, P(intercept), rand())

Leakers = No of inbound threats – intercepted threats

Input Parameters	
Incoming Air Threat	
Number of inbound Shell	60
Max Range (km)	7.2
Fired Range (km)	5.6
Muzzle Velocity (m/s)	315
Radar	
Effective Detection Range (km)	40
Apogee Ratio	0.4
Anti-Air	
Rate of Fire (rd/s)	60
Muzzle Velocity (m/s)	1110
Max Effective Range (m)	10000
Min Effective Range (m)	500
Process time for 1st launch (s)	4
P(Intercept)	0.2

Results	
Total Anti Air Munitions	159.64
Intercepted	***37***
Leakers	***23***
Timings	
Duration before impact (s)	17.78
Duration From Detect to Impact (s)	7.11
Duration from Launch to Impact (s)	3.11
Duration of Launch (s)	2.66

Figure 27. Snapshot of BOE computation model

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